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MOUNT WILSON AND PALOMAR OBSERVATORIES

CARNEGIE INSTITUTION OF WASHINGTON,
CALIFORNIA INSTITUTE OF TECHNOLOGY
Pasadena, California

Special Technical Report No. 2

ASTROPHYSICAL RESEARCH IN SPACE

by
Jesse L. Greenstein

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Jesse L. Greenstein

Mount Wilson and Palomar Observatories
Carnegie Institution of Washington
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INTRODUCTION

Astronomy will be one of many sciences to reap enormous gains from the possibility of carrying large payloads into space. That portion of astronomy concerned with the region where the earth's atmosphere merges into space, the region of upper air geophysics, has already provided enormous new insights. Balloon, rocket, satellite and space probes have till now been largely concerned with this intermediate zone. The present large, and proposed ultra-large payload vehicles make it possible to consider experiments of fundamental astronomical and physical significance in interplanetary space, where the earth is no longer the dominant body.

The rapid evolution, in planning at least, from the small satellite to the large vehicle, from payloads of 5 pounds to 5000 pounds, raises the question of the adequacy of our scientific planning, and the availability of both personnel and well-planned experiments. There are less than 500 astronomers in the United States, and the total operating budget of all observatories is about $5,000,000 per year (including considerable, but not major, Federal funds). The engineering personnel involved, and the dollar cost of one large vehicle far exceed the professional scientific staff and budget of all astronomy. Thus if we are to obtain full utilization of new possibilities, we must enlarge the scope of the astronomical community. At present a number of large astronomical institutions are involved in study, design and development of experiments in space; they include the new National Observatory (AURA), the University of Michigan, Princeton, and Harvard-Smithsonian. It is probable that one or more national centers will be created where experiments are translated into hardware and made compatible with the space, power and communications of the vehicle. It is certain that adequate engineering back-up must be provided for astronomers whose experimental problems, while certainly now difficult, are enormously different from those to be encountered in space. The major new experiments will also involve a close cooperation with laboratory physicists, because the new fields involve ranges of the energy spectrum not studied on earth. I sincerely hope that the rate of generation of new scientific ideas will keep pace with technology.

The question of the cost of space experiments assumes the proportions of a moral problem for an old-fashioned, earthbound astronomer like myself. One launching costs as much as our 200-inch reflector, the largest in the world. The large telescope has provided an enormous, as yet untapped range of possible experiments for a staff of a dozen professional astronomers for ten years; our 100-inch reflector is far from obsolete and is 40 years old. We cannot now attempt to justify the dollar cost of experiments in space, I believe, but we must make the most serious efforts to ensure that the research potentialities important for fundamental science be fully exploited. For this reason, my own thinking turns only to the "purest", most general problems; others will certainly carry out the "practical experiments". My philosophy of science and my reading of its history, convince me that the purest fields have been most productive in both scientific and dollar values. In brief, exploration for coal by a miner who knows what he is looking for, may easily miss diamonds. Therefore I will discuss a few of the important experiments on the border between physics and astronomy.

Astronomers are seriously hampered by the atmosphere.

(1) It absorbs large portions of the radio frequency, infrared, ultra-violet, X-ray and gamma-ray spectrum. Also affected are soft cosmic rays.

(2) The night airglow, fluorescence or chemi-luminescence in the ionosphere, provides a luminous background to the night sky and prevents very long exposures, either of photographs or spectra. It also limits the accuracy of photoelectric measurement. The daylight sky prevents study of the faint outer envelope of the sun.

(3) The turbulence in the atmosphere, through variations of density and water-vapor content, makes the index of refraction variable, in time and space. The result, twinkling of the stars caused by irregular propagation of the light-waves, is an unsteady

and unsharp image, averaging 1" (one second of arc) in very good night-time conditions, and almost never less than 0".2. Daytime conditions are worse. The erratic ionospheric refraction produces a twinkling and sporadic refraction of the radio stars.

(4) The earth's magnetic field acts as a shield for low-energy cosmic rays, and a storage trap for cosmic-ray secondaries.

Research from earth satellites is carried on at heights such that the first three of the difficulties listed above no longer exist. A major portion of most astrophysical research discussed till now can be carried out from large satellites at heights above 500 kilometers. Upper atmosphere geophysics will be supplemented by astrophysics above the atmosphere. I will discuss, below, the problems of an orbiting telescope, but there seems little reason to go above 500 km. The earth's magnetic and electric fields, the ionosphere, the density, composition, and temperature of the atmosphere can be studied below this height. Low-resolution cloud mapping, the infrared albedo of the earth and other meteorological studies can be carried out at ordinary satellite heights. Higher altitudes, probably 1000 to 15,000 km, are needed for the study of upper air heating, the Van Allen belts, the cosmic ray albedo and the cosmic ray primaries. But we may ask at what height we leave the earth and its influence and enter interplanetary space.

THE INTERPLANETARY PLASMA

The heating of the upper atmosphere by solar protons and electrons, cosmic rays, X-rays, etc. may ultimately be the energy source for ground-level weather. However, there is now little doubt that the upper atmosphere and exosphere are at a very high kinetic temperature (measured by the velocity of the atoms). Thus the density gradient is low, the scale height large and the atmosphere very extended. The present estimates of the interplanetary gas density is about 10^3 particles/cm^3, probably largely ionized hydrogen, protons and electrons. The upper atmosphere then grades imperceptibly into this substratum at very great heights--1,000 to 10,000 km. The earth's magnetic field decreases as the inverse cube, at large distances. Stray solar fields of 10^{-3} gauss may be carried by moving clouds of gas from the sun, so that the earth's regular dipole field may no longer dominate above 50,000 km. We might then set the lower boundary of the interplanetary plasma at say 100,000 km. The rotation of the earth's atmosphere and magnetic field produces an interaction with the interplanetary gas, and field, co-moving about the sun. The moon may produce some additional magnetic effects. It is probable that probes beyond the moon are the first to reach the genuine, undisturbed solar plasma. The outer boundary of the earth is not space, but the outer envelope of the sun!

The significant fact about the outer envelope of the sun is its enormous extension, which has its origin in the very high temperature of the outer layers. While the surface temperature is 6000°K, the layers at 10,000 km altitude are at 20,000°K and the low density corona is in the range 1 to 3 million degrees. This temperature inversion is connected, in as yet unknown ways, with the dissipation mechanisms of convection and turbulence of the sub-surface layers, or of the magnetic fields. This high temperature must be intimately connected with the mechanisms that produce soft cosmic rays on the sun, and is one manifestation of the general occurrence of "non-thermal" phenomena in the sun, stars, and interstellar space. About 10^{-4} to 10^{-6} of the total energy of the stars appears as high-energy protons and electrons, and in various manifestations of high temperature. The solar surface corresponds to an energy of about 1 electron volt, the chromosphere about 10 eV, the corona 500 eV and solar cosmic rays 0.5 Bev. The mechanism by which low energy is upgraded into high energy phenomena is unknown. The results, however, are unequivocally real. Several possibilities exist, the last frankly speculative.

(1) Fermi or betatron mechanisms in moving magnetic fields accelerate charged particles to high energies.

(2) Shock waves, ordinary or hydromagnetic, dissipate energy in regions of low density.

(3) An unknown fundamental mechanism exists in which large packages of energy may be stored in stellar material. (This position is taken by some Soviet astrophysicists.) Many stars show evidence of extreme non-thermal emission, and the Crab Nebula, a remnant of a supernova of 1054 A.D. shines by emission from relativistic electrons (of energies up to 10^{11} eV) in a magnetic field. These emit intense radio waves and also optical radiation. Thus we are extremely interested in any clues to the nature and amount of high-energy phenomena in space.

The outer corona of the sun evaporates into the relative vacuum of interplanetary space; the latter also may expand into interstellar space. This "solar wind" may fill interplanetary space with a substratum of as yet unknown temperature and density. Cooling mechanisms could lower its temperature, through inelastic collisions with atoms or dust grains; if not, the kinetic temperature may be a million degrees. We know only that the hydrogen is largely ionized (from Lyman-alpha emission observed in rocket flights). The measurement of the composition, level of ionization, density, velocity and temperature of the outer solar plasma is a fundamental experiment. Spectral lines of permitted atomic transitions in the far ultraviolet and X-ray region may be observable. (Incidentally, its spectrum should be like that of plasmas observed in laboratory thermonuclear devices.) In addition to this substratum, the sun ejects clouds of relatively high density, 10^5 ions/cm^3, with velocities of from 10^3 to 10^5 km/sec. These clouds exhibit some cohesiveness. When they reach the earth they envelope it, change the high altitude electric currents, cause magnetic storms, being guided by the earth's outer magnetic field. The nature of these ionized clouds, their density and their magnetic field can be studied only very far from the earth.

While the study of cosmic rays may be thought to be part of physics, their origin and energy supply is in astronomical bodies. I would like to discuss the astrophysical problem of the total energy contained in cosmic rays. Again the sun, as a typical star, gives us the most direct evidence. At the time of flares (energetic electromagnetic discharges in the solar atmosphere), some additional low energy cosmic rays reach the earth (with subsequent secondary phenomena). The earth's magnetic field screens off the lowest energies, except for impact zones at high latitudes, and the atmosphere (even 2 or 3 mm pressure) absorbs them strongly. The unaltered differential energy spectrum is of the form $N(E)dE = dE/E^n$, with n near 3. If we integrate over all energies from a low cutoff, E_o, to infinity, the total energy depends on E_o only, and the lower is E_o, the greater the total energy in the cosmic radiation. Energies below a few kilovolts are absorbed in the solar envelope, but only those of $E > 1$ Bev are observed at the earth. The power law spectrum is such, however, that there may be 10 to 100 as much energy above 10 Mev as above 1 Bev. Thus the total energy in cosmic radiation is not now determined from observation, and may be very large. Unless there is an unexpectedly large random magnetic field in planetary space, it is possible that the galactic cosmic rays of low energy traverse it unaltered and the true cosmic ray spectrum will become observable in space. In addition, the direct solar cosmic ray spectrum will be of great interest. The most satisfactory theory of origin of cosmic rays of high energy is that they have been accelerated by many collisions with moving magnetic fields in interstellar space. Do solar cosmic rays show the same spectrum? What is their variation in time and space? Are they produced directly at the sun by a different mechanism, or do stray fields between the planets provide the acceleration? Are low-energy cosmic rays from the sun and the stars injected into an interstellar acceleration mechanism? The problem of the total energy in cosmic rays is perhaps the most interesting, since we know that cosmic rays now in the Galaxy have a life of only a few million years in the Galaxy. The energy input of "non-thermal" nature is therefore large, and could be appallingly so.

The compositions of the normal solar plasma and of the heavy-element component of the cosmic rays are both of great interest. Very elaborate spectroscopic analysis of the sun and stars has given us a fairly good notion of their composition. Hydrogen is about 80 percent by weight, helium 18 percent, and the rest of the elements are present largely as traces, except for C, N, O, Ne which add up to about 1 percent. A planetary vehicle with a square meter area could collect one microgram in about a day, and a mass spectrographic analysis would be quite possible. Even the rarest elements would be represented by 10^6 atoms. Thus, scooping up a sample of the interplanetary gas might give us an analysis of the sun which has not yet baen possible in full detail. For example, stellar abundances of the isotopes are essentially unknown.

Knowledge of the heavy element component of the cosmic rays is of particular importance since it probably will determine the mode of injection into an acceleration mechanism, the nature of the acceleration and the lifetime of cosmic rays in the Galaxy. At the highest balloon altitudes the rays still traverse enough atmosphere to make it uncertain whether we observe only primaries or also some nuclear fragmentation products, notably lithium and beryllium. The latter nuclei, very rare in the stars, seem to be present in relatively high abundance at balloon altitudes. If these are true primaries from interstellar space, rather than secondaries produced in the upper atmosphere, then their origin must be fragmentation of the heavy nuclei from neon to iron in space, i.e. these heavy nuclei have only a short life span and end, largely as protons and alpha particles. If so, again the total input energy for continued generation of cosmic rays is increased. For such studies, a large vehicle in interplanetary space is required; the weight of the experiment is not prohibitive, but the sophistication of the equipment and the time duration required will be very great.

THE ORBITING TELESCOPE

Two astronomical aspects of space experimentation have been stressed -- the possibility of high-resolution photography outside the atmosphere and the wider range of energy spectrum. Balloon flights with a 16-inch diameter mirror have been successfully carried out and solar photography obtained at the theoretical maximum resolution of 0".25. Such resolution is rarely, but sometimes, attained on the earth, but unless a factor of two or more in resolution can be gained there is little point in orbiting such elaborate equipment as a telescope, with readout system and guidance, both good to better than a fraction of a microradian. Thus, mirror diameters of 40 inches and equivalent focal lengths of 12 feet are a minimum. (The actual tube length can be a good deal less.) Solar photography requires exposures of 1/1000th of a second, so guidance accuracy need not be very great. But planetary photography is of a different order of magnitude of difficulty.

Exposure times are, for the ordinary spectral regions, about 1/10th of a second, and would be long for far infrared or ultraviolet. Thus guidance and rate accuracy must be much better than 10 microradians/second. Target acquisition also is difficult--some pessimists feel that only a manned vehicle (or a lunar observatory) will suffice. But solar, lunar and planet photography may be attainable without this, and the major problems arise in the communications link, for non-recoverable experiments. The same problem is even more serious for very high resolution photography, on near passage of moon or planets, because of the larger amount of information and the great distances to be covered.

Since we are ignorant of the size of detail in unfamiliar spectral regions, exploratory photography of the sun and planets with smaller telescopes will at first be sufficient. An ultraviolet photograph of the sun in the emission line of hydrogen, Lyman alpha, should contain about 10^7 bits of information. To follow details of solar activity, in which some features change in a few minutes, would again strain the communication link. Acquisition and guidance on the sun are, of course, the easiest of the space-telescopes assignments. But the largest task of an initially small orbiting telescope will be that of obtaining ultraviolet and X-ray spectra of the sun and of the stars. Excellent work on the sun has been done from rockets, largely by the Naval Research Laboratory, but they have been limited to exposure times of a minute or less. The orbiting spectrograph will have an indefinite exposure time, may scan features of the spectrum of the sun, and the corona, with very high resolution and also observe their temporal variations, connected with the solar activity. The temperatures of the sun indicated by emission lines in the rocket ultraviolet corresponded to about 50 eV; coronal features should occur up to 500 eV. It is also already known that solar coronal X-ray emission exists and is rapidly variable, initiating radio fadeouts and other variations of the ionospheric ionization. Rocket experiments have only coarsely analyzed these X-rays, using penetration of different metal foils to obtain their approximate wavelengths, and have shown that emission occurs up to 1000 eV. An X-ray scanning and recording spectrophotometer is needed for proper identification of the chemical elements responsible, their temperature and location on the solar disk or coronal envelope.

To the astronomer, however, a most exciting prospect is offered by the first, even low resolution spectra of other types of stars. The ultraviolet spectra from 4 eV to 13 eV will contain many surprises. The first question would be whether other stars show the same peculiar temperature inversion that the sun does. Do they all have coronas of a million degrees temperature, or are such non-thermal envelopes peculiar and rare? Do hotter stars have hotter envelopes? Some of these questions will be answered easily; but in addition to the technical difficulties of locating and locking on a particular star, another serious difficulty exists which makes a large part of the ultraviolet opaque, even from above our atmosphere. Hydrogen, the most abundant element in the universe, exists throughout interstellar space near the sun with a mean density of one neutral atom per cubic centimeter. This near vacuum, however, is highly absorbing over a continuum of energies above the ionization potential of hydrogen, 13.54 eV ($\lambda < 912A$). Across a distance of one light year, the optical depth is 10 (i.e. the light is weakened by e^{-10}). Thus, if the neutral hydrogen forms a homogeneous screen around the sun, our penetration of space will be small and only a few (and rather uninteresting) stars will be observable. The opacity drops roughly as $1/E^3$, so that the further ultraviolet is much more accessible. However, to reach stars at 1000 light years distance the long wave limit of the stellar spectra will be about 30 A or 400 eV. Thus the ultraviolet properly consists of two ranges -- the optical from 2900 A to 912 A, and the X-ray below 30 A. The very interesting resonance line of hydrogen, Lyman alpha, will be partly obscurred by the interplanetary emission. Since experimental techniques are relatively very difficult in the X-ray range, a considerable laboratory research and development program is needed.

The infrared and radio frequency ranges do not have any such barriers until the frequency drops below the plasma frequency in space. The latter is so low that probably the interplanetary rather than interstellar gas sets the long wave limit of the radio spectrum that may be explored.

Ultra-high energy photons, γ-rays, will be of considerable interest. Telescopes are no longer useful, but large, directional photon-sensitive counter arrays will be needed. There are some theoretical reasons for expecting the γ-ray produced by the destruction of deuterium by protons; the annihilation γ-rays may also appear. The sun may produce γ-rays in solar flares, and some large gaseous nebulae, especially those which are strong radio sources, may be powerful γ-ray emitters.

The photography and spectroscopy of the planets, ultraviolet mapping of the Milky Way and innumerable other problems have been suggested, and will be carried out. The list is already large. The new, larger vehicles suggest the need for problems of a more general and no longer geocentric nature. Cosmological experiments are under development to test, for example the contraction of the time coordinate in a rapidly moving body. Accurate orbital data, on a drag-free satellite in a highly eccentric orbit, may provide a test of even the general theory of relativity. The luminosity of the background of unresolved light from extragalactic nebulae at very large distances has been suggested as a test of theories of the line-element in relativistic cosmological models.

What actually will be accomplished, and how much will be learned, will depend on the simultaneous growth of rocket technology, of scientific imagination and of increased good luck at launching!